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An Investigation on the Sandwich Panels with Flexible and Toughened Adhesives under Flexural Loading

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Abstract**—**The material selection in the design of the sandwich structures is very crucial aspect because of the positive or negative influences of the base materials to the mechanical properties of the entire panel. In the literature, it was presented that the selection of the skin and core materials plays very important role on the behavior of the sandwich. Beside this, the use of the correct adhesive can make the whole structure to show better mechanical results and behavior. In the present work, the static three-point bending tests were performed on the sandwiches having an aluminum alloy foam core, the skins made of three different types of fabrics and two different commercial adhesives (flexible polyurethane and toughened epoxy based) at different values of support span distances by aiming the analyses of their flexural performance in terms of absorbed energy, peak force values and collapse mechanisms. The main results of the flexural loading are: force-displacement curves obtained after the bending tests, peak force and absorbed energy values, collapse mechanisms and adhesion quality. The experimental results presented that the sandwiches with epoxy based toughened adhesive and the skins made of S-Glass Woven fabrics indicated the best adhesion quality and mechanical properties. The sandwiches with toughened adhesive exhibited higher peak force and energy absorption values compared to the sandwiches with flexible adhesive. The use of these sandwich structures can lead to a weight reduction of the transport vehicles, providing an adequate structural strength under operating conditions.

Keywords**—**Adhesive and adhesion, Aluminum foam, Bending, Collapse mechanisms.

I. INTRODUCTION

SANDWICH composite constructions manufactured via bonding of two thin but stiff skins and a low density but thick core offer widely potential use in aerospace, automotive, marine, defense and other industrial applications. These lightweight materials, replacing them with the conventional ones, enable to reduce fuel consumption, to increase load carrying and energy absorption capacities, to provide more safety of crafts and to obtain higher speed, particularly, in transport industry (automotive, shipbuilding and aerospace industry).

In order to obtain weight minimized structures, the sandwiches based on polymeric foams (such as PVC, PUR) bonded to fiber reinforced polymer (FRP) skins have been investigated for many years. Recently, there are a great number of metal foams developed to replace polymeric ones in applications where multifunctionality is an important aspect. For instance, metal foams take part not only as a structural component in a sandwich composite but also as an acoustic damper, fire retardant or heat exchanger [1]. As a new multi-function engineering material, aluminum foams have many useful properties such as low density, high stiffness, good impact resistance, high load carrying and energy absorption capacities, easy to manufacture into complex shape, good erosion resistance, etc. [2], [3]. This fact exhibits a wide range of potential applications for sandwich panels with aluminum foam core. Aluminum foam cored sandwiches with various face materials (aluminum, glass fiber reinforced plastic, thermoplastic etc.) [4]-[6] are suitable for applications in automotive industry and ship construction [7], as they allow a speed increase and safety of vehicle with good passenger comfort thanks to their specific weight and high energy absorption capability.

Sandwich structures can fail with different collapse mechanisms under static and dynamic loading conditions, depending on the physical and geometrical properties of their components [8], [9]. The failure model of a sandwich with metallic foam core has been established by some of the authors [9], [10] and they estimated the failure expected to result by several modes (i.e. face yield, core shear, indentation and face wrinkling) corresponding to the minimum collapse loads, depending on the deformation forms. Their model has been confirmed by multiple parallel studies [11]-[14]. Moreover, it has been investigated that the most of the sandwiches failed due to core shear during flexural loading [4], [15], [16]. These researchers also presented that the use of adhesive and adhesion techniques can affect the behavior of entire sandwich panel. Using these collapse models, some of the authors [10], [11], [14], [17]-[19] reported failure mode maps which represent a useful tool for practical design of sandwich beams [20] in order to determine the dominant mode.

The aim of this study was the analysis of flexural behavior of the sandwiches obtained via bonding of the glass fiber reinforced polymer (GFRP) skins to an aluminum alloy foam core with the use of flexible and toughened adhesives and the comparison of the results respect to the influence of the variety of the skin type and the adhesive type to the entire panel in terms of absorbed energy and peak force values. The

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skins can be easily bonded to the sandwich and it is possible to design the best configuration (base materials, fiber angle orientation and number of layers) for a specific application. Vacuum Assisted Resin Transfer Molding (VARTM) method was used to produce the GFRP skins consisting of three different types of [0º/90º] oriented glass fabrics (E-Glass Woven, E-Glass Biaxial Stitched and S-Glass Woven) and Bisphenol A based epoxy resin (Araldite® LY 1564/Aradur® 3487). The skins were bonded onto the aluminum core using two different commercial adhesives (SikaFlex-265 polyurethane based flexible adhesive and Loctite 9461A&B epoxy based toughened adhesive). The bonding process was performed using a press machine in order to obtain uniform adhesion thickness throughout the panel and to remove the air inside the adhesive. The static three-point bending tests were performed on the sandwich specimens by a universal testing machine with different values of support span distance (L = 55, 70, 80 and 125 mm) in order to determine its influence to the collapse modes.

II. MATERIALS AND METHODS

The sandwich specimens were made bonding of two GFRP skins to aluminum alloy foam core (Alulight® International GmbH) with the use of flexural and toughened commercial adhesives (SikaFlex-265 and Loctite 9461 A&B) under press machine with the pressure of 0.01 bar in order to obtain uniform adhesion thickness throughout the panel and to remove the air inside the adhesive. In the bonding process, firstly, one skin material was bonded to one of the surface of aluminum foam core under press machine using a steel alignment plate with the thickness containing the sum of one skin (about 1.5 mm), core (10 mm) and one adhesive (about 0.5 mm) thicknesses. For the curing of first adhesion, it has been waited for about three hours. Then, another skin was bonded to another surface of the core under same pressure value using a secondary steel alignment plate produced respect to the total thicknesses of the whole panel. For the curing of second adhesion, the press machine was held under same pressure value about three hours.

The skins made of three different [0º/90º] oriented glass fabrics (3 layers of E-Glass Biaxial Stitched, 3 layers of E-Glass Woven and 8 layers of S-Glass Woven with the areal densities of 450 g/m^2, 500 g/m^2 and 190 g/m^2, respectively) and a Bisphenol A based epoxy resin (Araldite® LY 1564) with a hardener (Aradur® 3486) in a mixture ratio by weight of 100/34 were produced via VARTM which is also known as Vacuum Infusion. For the curing of resin, aluminum lay-up surface was heated up 100 ºC during two hours. In order to identify the sandwich typologies used in the study, some of the abbreviations were done representing the base materials of a panel as shown in Fig. 1.

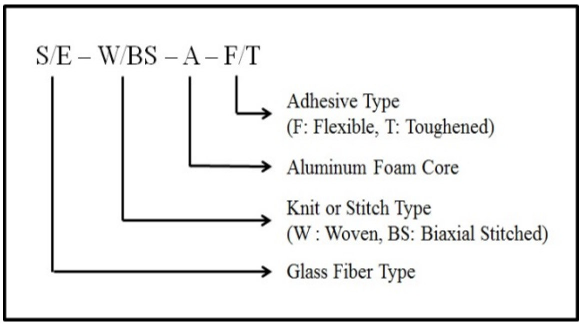

Fig. 1 Identification of sandwich typologies used in the study respect to the base materials

The physical and geometrical properties of the investigated panels and their base materials are reported in Table I.

TABLE I
PHYSICAL AND GEOMETRICAL PROPERTIES OF SANDWICH PANELS

Sandwich Typology	Skin			Core			Adhesive		
	Material	Density [kg/m^3]	Thickness [mm]	Material	Density [kg/m^3]	Thickness [mm]	Material	Density [kg/m^3]	Thickness [mm]
EBSAF	E-Glass Biaxial Stitched Fiber/Epoxy Resin	1440	1.5	AlSi10	530±60	10	SikaFlex-265	1200	0.5
EBSAT	E-Glass Biaxial Stitched Fiber/Epoxy Resin	1440	1.5	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5
EWAF	E-Glass Woven Fiber/Epoxy Resin	1480	1.5	AlSi10	530±60	10	SikaFlex-265	1200	0.5
EWAT	E-Glass Woven Fiber/Epoxy Resin	1480	1.5	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5
SWAF	S-Glass Woven Fiber/Epoxy Resin	1580	1.5	AlSi10	530±60	10	SikaFlex-265	1200	0.5
SWAT	S-Glass Woven Fiber/Epoxy Resin	1580	1.5	AlSi10	530±60	10	Loctite 9461A&B	1400	0.5

The static three point bending tests were carried out on the sandwich specimens with the same nominal size (150 x 50 x 14 mm) using a servo-hydraulic universal load machine. All the tests were performed on the panels after one week of the production of the entire sandwiches in order to support the best performance of the adhesives. The failure mode of the panels under bending load applied at different values of support span distances (L = 55, 70, 80, 125 mm) and the damage of the specimens have been also investigated as reported by some of the authors [6], [9], [19], [21].

III. RESULTS AND DISCUSSION

Static three-point bending tests were realized on the sandwich panels using a servo-hydraulic load machine. The load was applied at a constant rate of 2 mm/min and with a preload of 20 N. The tests were performed on the specimens at different values of the support span distances (L = 55, 70, 80, 125 mm). Figs. 2-7 show the load-deflection curves obtained from bending tests carried out on all the sandwich typologies with different GFRP skins and adhesives.

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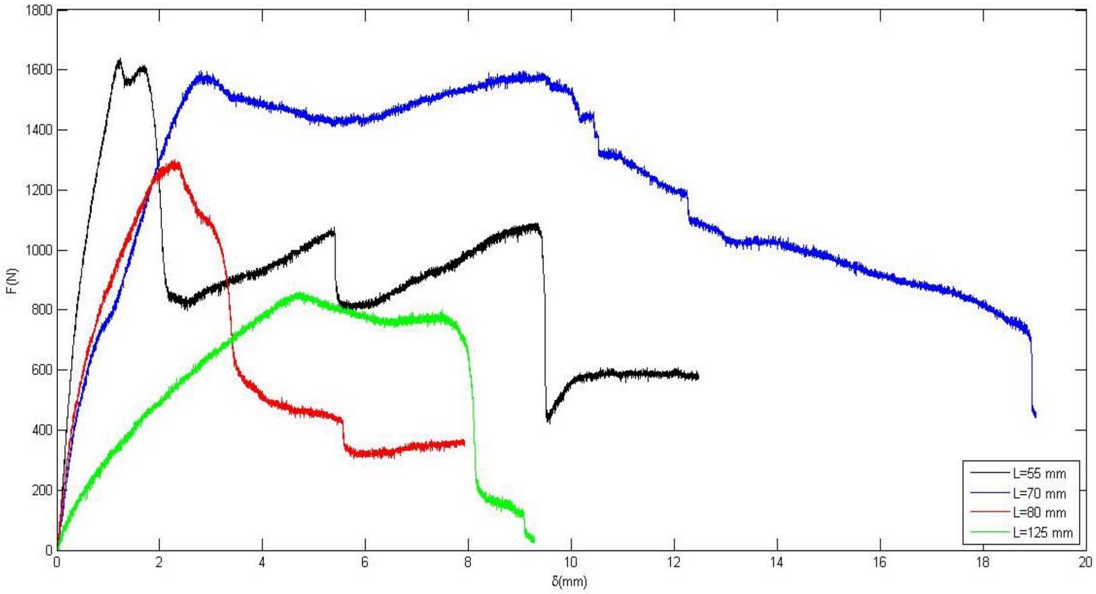

Fig. 2 Load - deflection curves measured under static three-point bending for the sandwiches named EBSAF

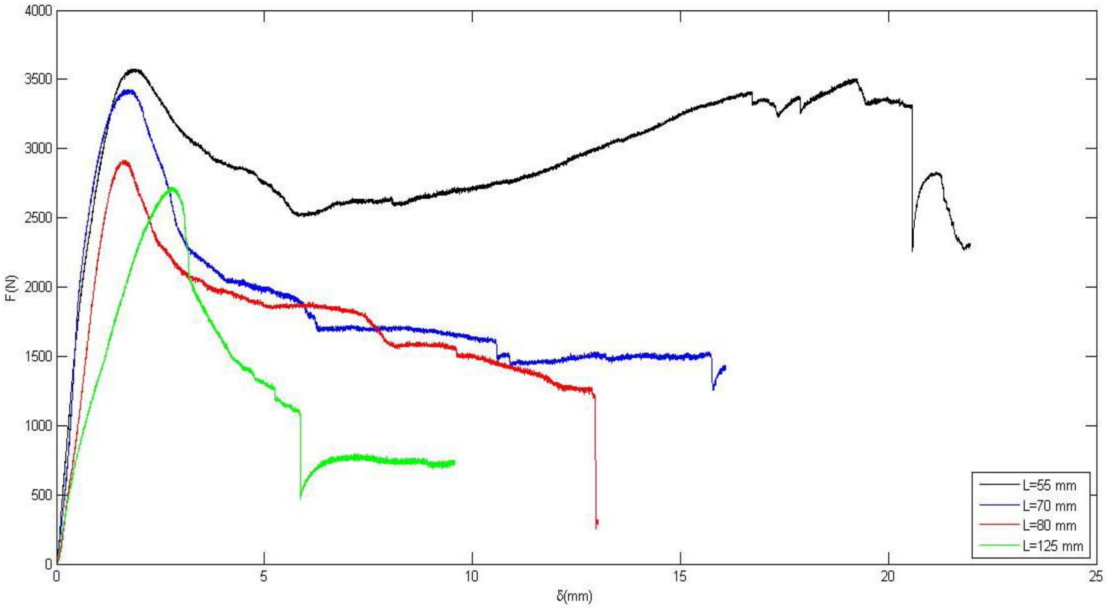

Fig. 3 Load - deflection curves measured under static three-point bending for the sandwiches named EBSAT

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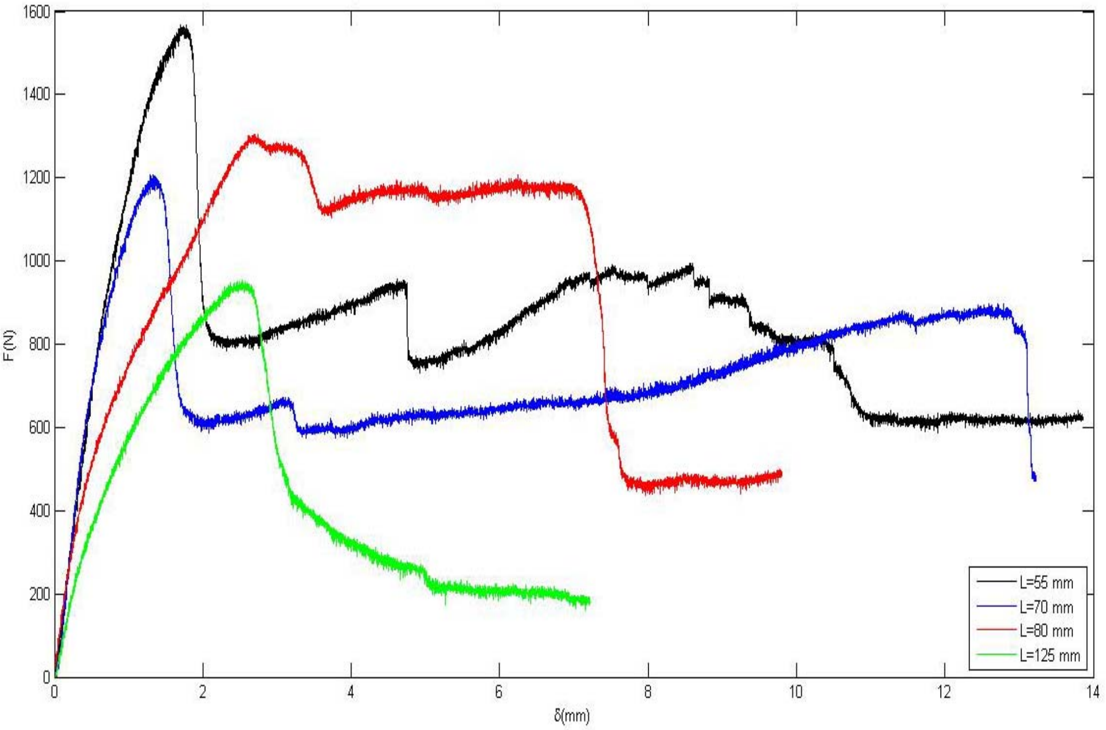

Fig. 4 Load - deflection curves measured under static three-point bending for the sandwiches named EWAF

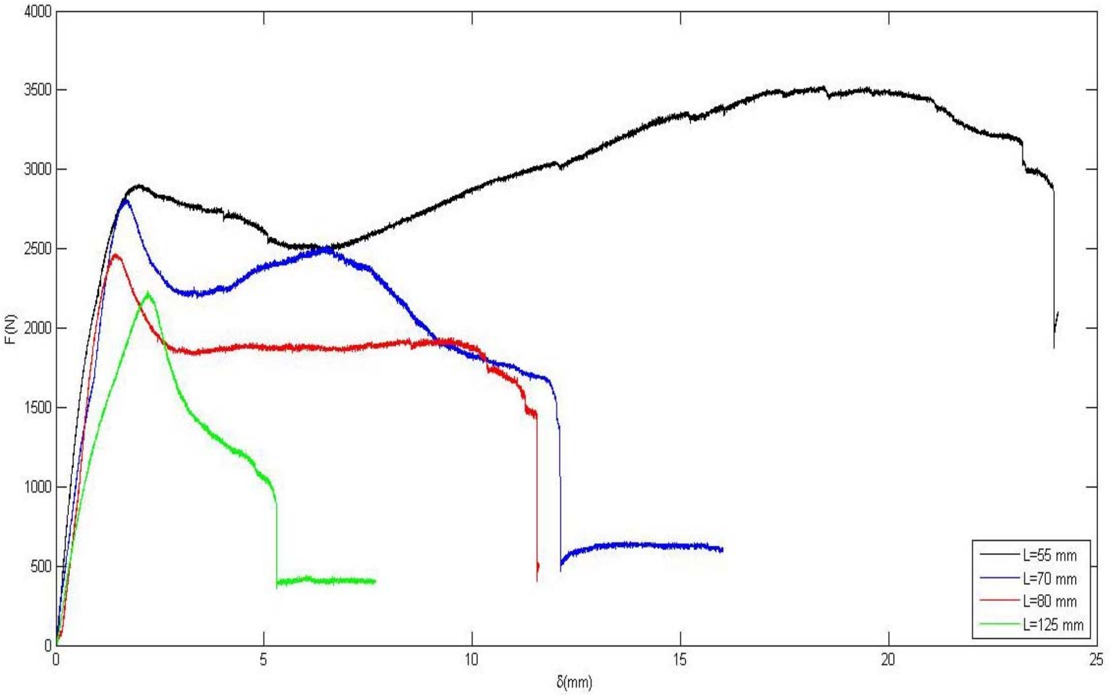

Fig. 5 Load - deflection curves measured under static three-point bending for the sandwiches named EWAT

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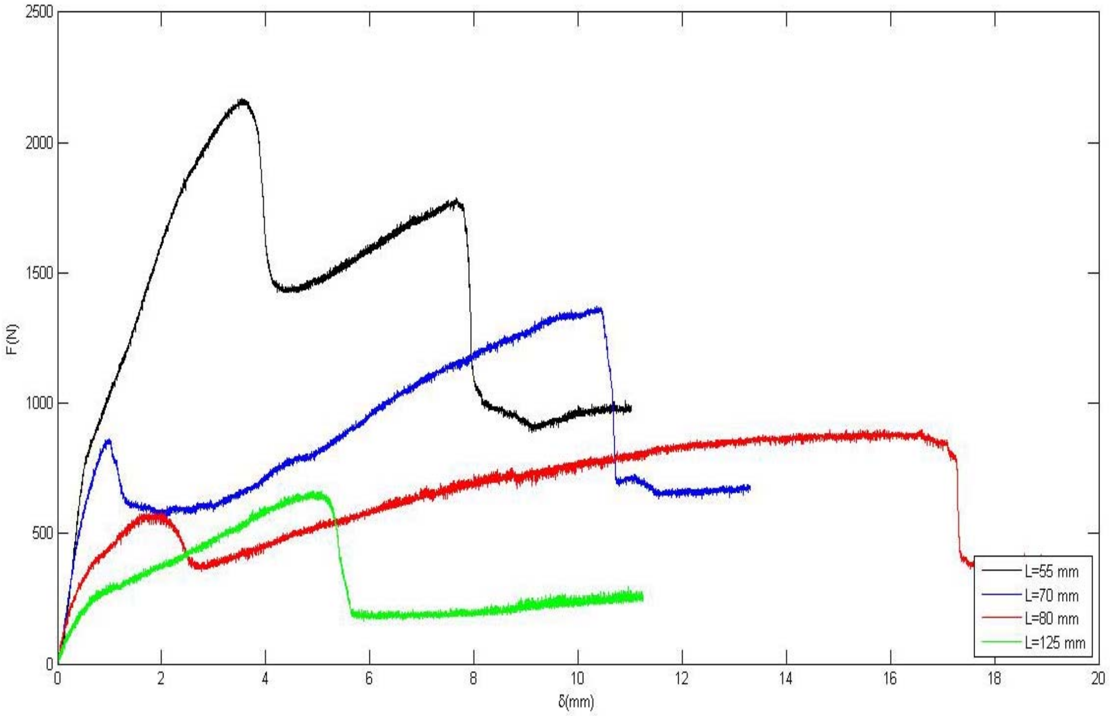

Fig. 6 Load - deflection curves measured under static three-point bending for the sandwiches named SWAF

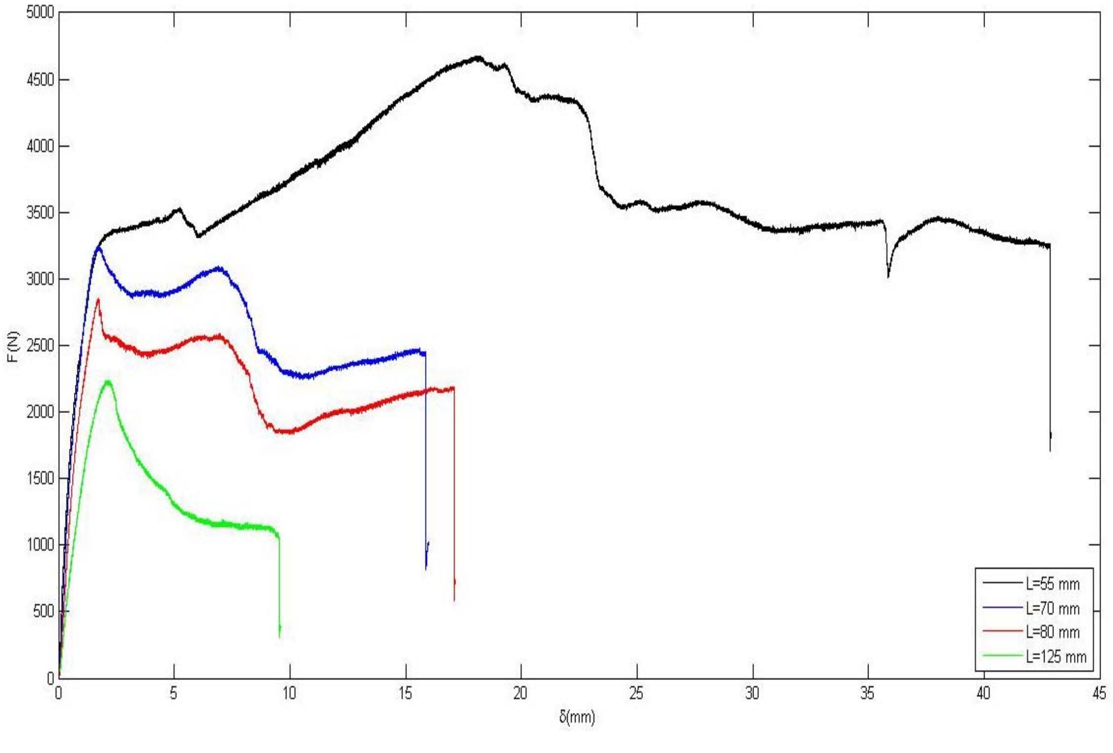

Fig. 7 Load - deflection curves measured under static three-point bending for the sandwiches named SWAT

All the sandwich specimens collapsed after the bending tests are presented in Figs. 8-13.

Fig. 8 Collapsed sandwiches named EBSAF after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 9 Collapsed sandwiches named EBSAT after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 10 Collapsed sandwiches named EWAF after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 11 Collapsed sandwiches named EWAT after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 12 Collapsed sandwiches named SWAF after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

Fig. 13 Collapsed sandwiches named SWAT after the bending tests at different support span values (top to bottom: L = 55, 70, 80 and 125 mm)

From Figs. 2-7, it is clear that all the sandwiches exhibit initial linear-elastic behavior which is followed by an elasto-plastic phase, due to the permanent plastic deformation of the aluminum alloy foam core. Afterward, the load decreases initially markedly for all the sandwich typologies because of the shear of the core. And then, the following different scenarios occurs because of the use of different types of adhesive and skin for the sandwich typology named,

- *EBSAF*: The load tends to decrease up to second abrupt load loss due to the partial debonding of the lower and/or upper skin (Fig. 8) for the specimens at L = 70, 80 and 125 mm while the load fluctuates twice up to final debonding of the lower skin (Fig. 8) for the sandwich at L = 55 mm.
- *EBSAT*: The load tends to decrease up to second abrupt load loss due to the partial debonding of the lower or upper skin (Fig. 9) for the specimens at L = 70, 80 and 125 mm while the load tends to increase up to the brake of the upper skin (Fig. 9) for the sandwich at L = 55 mm.
- *EWAF*: The load remains almost constant for all the support span values up to the second abrupt load loss due to the debonding of the lower skin (Fig. 10).
- *EWAT*: The load remains almost constant up to the second abrupt load loss due to the debonding of the lower skin (Fig. 11) for the sandwiches at L = 70, 80 and125 mm while the load tends to increase up to the second abrupt load loss due to the failure of lower skin (Fig. 11) for the specimen at L = 55 mm.
- *SWAF*: The load tends to increase up to its maximum value for the specimens at L = 70 and 80 mm and finally debonding of the lower skin (Fig. 12) occurs at the second abrupt load loss while the sandwiches at L = 55 and 125 mm exhibit almost constant value of the load up to the second abrupt load loss due to the debonding of the lower skin (Fig. 12).
- *SWAT*: The load remains almost constant for all the support span values up to the second abrupt load loss due to the debonding of the lower skin (Fig. 13).

The failed sandwich specimens exhibit a significant permanent global deformation of the panel and core shear failure away from the loading points. Three point bending tests carried out by [6] on sandwich panels based on aluminum foam core and different types of composite skins revealed that the panels failed by different mechanisms and this suggests that a proper selection of the composite skin significantly influences the overall failure mode of the sandwiches and high capacity of absorbing energy.

Some theoretical models were developed by [9], [19] to predict the failure mechanism of sandwiches. These authors have been particularly concerned with foam core sandwiches. Assuming a perfect bond between the faces and the core and eliminating the possibility of delamination, sandwich beams can fail by several modes in bending tests: core shear, face yield, indentation and face wrinkling.

The observed collapse mechanism of the sandwiches analyzed in the study which wasn't affected by the support span length and the types of the skin and adhesive occurred as core shear for all the sandwich typologies, as seen from Figs. 8-13.

The amount of the energy absorption E was evaluated integrating the load - deflection curves, obtained by the bending tests. The values of energy efficiency η were considered in order to compare the bending tests at different support spans L. The efficiency is defined as the absorbed energy up to failure deflection $\delta_{\max}$ normalized by the energy absorption of the ideal absorber [22]:

$$\eta = \frac{E}{E_i} = \frac{\int_0^{\delta_{\max}} F d\delta}{F_{\max} \cdot \delta_{\max}} \tag{1}$$

where $F_{\max}$ is the highest force occurred during the bending test. The average values of the bending test results corresponding to the sandwich typologies are reported in Table II.

TABLE II
RESULTS OF ALL THE BENDING TESTS

Sandwich Typology	L = 55 mm			L = 70 mm			L = 80 mm			L = 125 mm		
	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]	F_{max} [N]	E_{abs} [J]	η [%]
EBSAF	1641	11	54	1597	23	75	1300	5	49	863	5	65
EBSAT	3575	64	82	3425	30	54	2916	23	60	2722	12	47
EWAF	1566	12	53	1206	10	60	1303	9	70	953	3	44
EWAT	3525	71	84	2813	28	62	2472	21	73	2238	8	48
SWAF	2169	15	63	1372	11	63	900	12	72	663	4	48
SWAT	4675	157	78	3256	41	79	2856	37	76	2241	13	61

The experimental results confirm that the ability to absorb energy of the sandwiches with aluminum alloy foam core is obviously affected by the type of skin and adhesive and the support span value. The best response in terms of energy efficiency, as reported in Table II, was obtained for the sandwich typologies having toughened epoxy based adhesive, subjected to bending loads with support span value of L = 55 mm. It is due to the peak force value which was influenced by the adhesive type, adhesion quality and the type of glass fiber skin and hence the higher rigidity of the whole panel that was affected by the support span length.

IV. CONCLUSIONS

The study presented in this paper is part of a larger project aimed at the introduction of lightweight structures, made of the sandwiches with aluminum alloy foam core, in the

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transportation industry (automotive, aerospace, shipbuilding industry).

The flexural responses of the sandwiches with aluminum alloy foam core were investigated and the results were compared respect to the variety of the GFRP skins and adhesives and also support span values in terms of peak load and absorbed energy.

The experimental tests have demonstrated that the light-weight sandwiches with aluminum foam core and GFRP skins are efficient energy absorbers and that the amount of energy absorption under bending tests can be improved using better base materials (skin, core and adhesive), which can be designed according to the application of the sandwich. From the results of the analyses, the sandwiches having S-Glass skins and toughened epoxy based adhesive layers presented the best flexural response. The support span distance can also affect energy absorption capacities.

The future developments of this study consist of the analysis of the failure maps of these sandwiches subjected to the three point bending test.

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